

The University of Chicago

A STUDY OF THE NICKEL
INTRUSIVE, SUDBURY, ONTARIO

A DISSERTATION SUBMITTED TO THE FACULTY
OF THE DIVISION OF THE PHYSICAL SCIENCES
IN CANDIDACY FOR THE DEGREE OF DOCTOR
OF PHILOSOPHY

DEPARTMENT OF GEOLOGY AND PALEONTOLOGY

1935

By

ROBERT THOMSON

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NICKEL ERUPTIVE OF SUDBURY,
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NICKEL ERUPTIVE OF SUDBURY, ONTARIO¹

BY ROBERT THOMSON

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The term "Nickel Eruptive" was applied by A. P. Coleman² to the norite and associated micropegmatite rock occurring near Sudbury. In traversing the Eruptive from outer to inner contact, one everywhere crosses a basic rock (norite), and then an acid one (micropegmatite).

Doctor Walker,³ one of the early investigators in the district, suggested that norite and micropegmatite had formed by the differentiation *in situ* of a parent magma. This theory was accepted by numerous later workers, among whom Coleman has been its outstanding proponent. This hypotheses has, however, been questioned, particularly by Phemister,⁴ who, came to the conclusion that norite and micropegmatite are separate intrusions. In the present article attempt is made to test these alternative hypotheses.

In the course of field-work, the norite and micropegmatite, and the transition zone between them, in the southwestern part of the eruptive area were mapped. Numerous thin-sections were examined.

It was found impossible to measure, or even to estimate with any degree of accuracy, the relative amounts of the minerals now present in thin-sections of the Eruptive. The original minerals which crystallized from the magma have in most places been transformed partly, or completely, into new minerals. Attempt was made, however, to determine the relative amounts of the original minerals; thus, even though a plagioclase crystal was largely altered to epidote, albite, etc., it was recorded as plagioclase. Mafic minerals were not measured separately. Amphibole in many places is

¹ Published with the permission of the Director of the Geological Survey of Canada.

² Journal of Geology, Vol. XV, p. 763, 1907.

³ Quart. Jour. Geol. Soc., London, Vol. LIII, p. 40, 1897.

⁴ Thirty-fourth Ann. Rept., Ontario Dept. of Mines, Pt. VIII, 1925.

evidently secondary after pyroxene, but the proportion of pyroxene present originally could not be accurately determined. Quartz-feldspar intergrowths are so intimate that the component minerals were not estimated separately.

A geological map of the Nickel Eruptive, between Trill and Creighton townships, is shown in figure 18. Norite grades through a relatively narrow transition zone into micropegmatite. The transition zone is not visible in many places due to overlying till. The mineral compositions of norite, transition zone-rock, and micropegmatite, as shown by thin-sections, are given in table I.

In the column headed "andesine-labradorite" are given the percentages of plagioclase occurring in nearly euhedral crystals in norite. The composition is about Ab_1An_1 in the central parts of the crystals but the outer parts are richer in albite. Alteration is usually extensive.

The column headed "plagioclase pseudomorphs" refers only to transition zone-rock. In it the original plagioclase is completely altered to new minerals, principally epidote, albite, and quartz.

The column headed "albite-oligoclase" refers to the more or less euhedral plagioclase crystals in the micropegmatite rock.

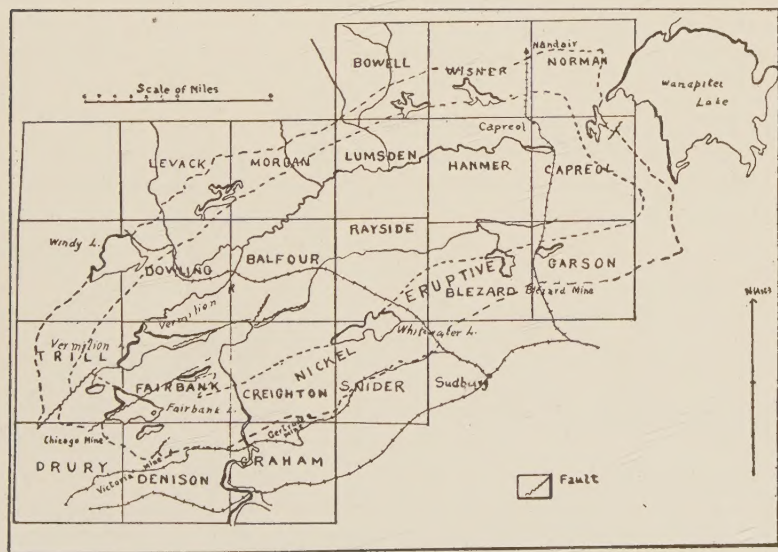


Figure 17. Sketch-map of Nickel Eruptive District.

TABLE I

Mineral Compositions of Norite, Transition Zone-Rock, and Micropegmatite.

	Andesine- labradorite	Plagioclase pseudomorphs	Albite- oligoclase	Mafic minerals	Quartz-feld. intergrowths	Accessory minerals
<i>Norite:</i>						
Matrix to breccia, outer contact						
Trill township	45			50	5	
North of Cameron Creek fault	47			20	31	1
	47			19	33	1
Between Cameron Creek and	58			23	18	1
Fairbank Lake faults	55			21	23	1
	54			24	20	2
	55			20	25	
	52			21	26	1
	57			23	20	
	47			21	29	2
	44			26	29	1
	46			23	31	
South of Fairbank Lake	51			26	23	
	40			30	30	
Between Chicago and Victoria	60			27	13	
mines	60			30	20	
	60			15	25	
	60			27	15	
Near outer contact	46			29	25	
	40			45	15	
Victoria mine to Gertrude mine	55			32	13	
About ½ mile from outer contact	60			30	10	
About 1 mile from outer contact	50			47	3	
About 1½ mile from outer contact	61			26	10	
<i>Transition zone:</i>						
Between Cameron Creek and		44		16	36	4
Fairbank Lake faults		38		15	35	2
		36		14	49	1
South of Fairbank Lake		40		30	30	
		45		15	40	
		55		15	25	
		35		25	40	
		35		23	42	
<i>Micropegmatite:</i>						
North of Cameron Creek fault			32	20	48	
			32	14	43	
			39	14	44	3
			40	10	50	
			40	9	50	
Near Fairbank Lake			40	5	55	
			30	15	55	
			40	9	51	
North of Victoria mine			37	16	47	
			45	20	35	
Fairbank and Creighton Twps.			55	20	30	
			20	10	70	
			30	12	58	

Under "quartz-feldspar intergrowths" is included the quartz of the norite, where typical intergrowths are often in very small amount.

Accessory minerals include magnetite, ilmenite, apatite, and orthite.

A special traverse was made along the Canadian National railway, between Capreol and Nandair, in the Northern range. Phemister ⁵ had previously described the rocks along this section; and more recently Coleman, Moore & Walker ⁶ published a number of chemical analyses of the rocks there. No contact, nor transition zone between norite and micropegmatite was found.

The mineral compositions, as shown by Rosiwal analyses of the sections collected by the writer are shown in figure 19a. Through the courtesy of Doctor Walker the writer had access to thin-sections of the specimens from which the analyses given by Coleman, Moore & Walker were made. The writer's estimates of the mineral compositions of these are shown in figure 19b.

Through the courtesy of Doctor Walker the writer also had opportunity of examining thin-sections of the specimens collected along the main line of the Canadian Pacific railway, across the Eruptive, near the Levack mine, from which the analyses given by Coleman, Moore & Walker were made.⁷ Estimates of the mineral composition are shown in figure 20. The position of the transition zone is indicated by the broken line.

Estimates of the mineral composition of thin-sections of specimens from which the analyses given by Coleman, Moore & Walker were made, for the section across the Eruptive, north of Creighton mine, are shown in figure 21. The position of the transition zone is indicated by the broken line.

TABLE II

Composition of Norite near Blezard Mine

Distance from Outer Contact (in feet)	500	200	100	50	15	5
Labradorite	68	48	45	30	48	5
Mafic minerals, Pyroxene	13	12				
Amphibole	14	12	25	20	30	95
Biotite	3	16	18	15	15	
Quartz	1	11	12	35	7	
Magnetite						

⁵ *Loc. cit.*, Pt. 8, p. 7, 1925.

⁶ University of Toronto Studies, p. 24, 1929.

⁷ *Loc. cit.*, p. 26.

About 100 feet from its outer contact, the norite, which farther out appeared uniform, shows variations within short distances. The norite within 500 feet of its outer contact is variable in the kind and amount of minerals contained and in the amount of alteration. The passage of this modified norite into the more usual phase is gradational. The usual norite contains a higher percentage of plagioclase than its basal modification. Although the central parts of the crystals in each is of about the same composition (about $\text{Ab}_{45} \text{An}_{55}$), in the former they are very slightly zoned, whereas in the

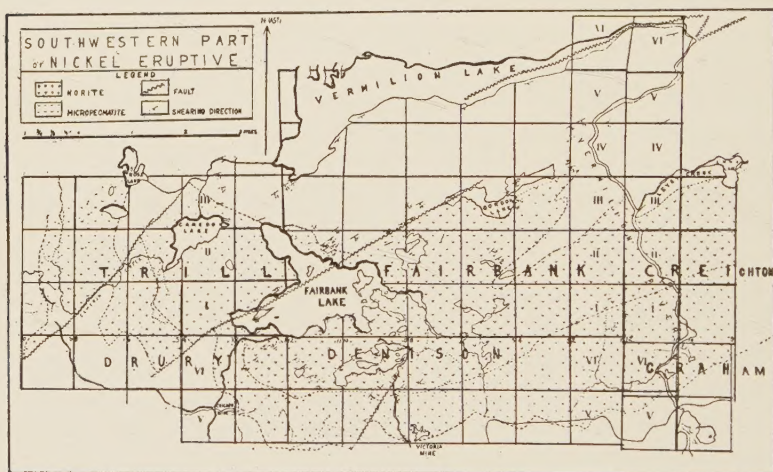


Figure 18. Geology of Southwestern Part of Nickel Eruptive Area.

latter they are markedly zoned and thus more alkaline. The usual norite contains orthorhombic and monoclinic pyroxenes; in the modified norite these are not present nor does it appear probable they ever were present in as large amounts as in the norite farther inwards. Quartz is in much lower percentages in the usual norite than in its basal modification. Biotite and amphibole replace the other minerals to a much greater extent near the contact than farther inwards. The amount of biotite present in the norite varies sympathetically with the amount of quartz. It is noteworthy that while the amount of quartz is large, it is not accompanied by marked alteration of the plagioclase to epidote, white mica, or albite.

If the Nickel Eruptive be traversed from the outer to the inner contact, a belt, of variable width, of norite characterized by ande-

sine-labradorite up to about 65%, quartz-feldspar intergrowths up to about 30%, and mafic minerals up to about 45% is crossed first. After this is a narrow belt, a few hundred yards wide of transition zone-rock, in which completely altered plagioclase crystals, possibly medio-basic originally, make up to about 45%, quartz-feldspar intergrowths up to about 50%, and mafic minerals up to 25% of the

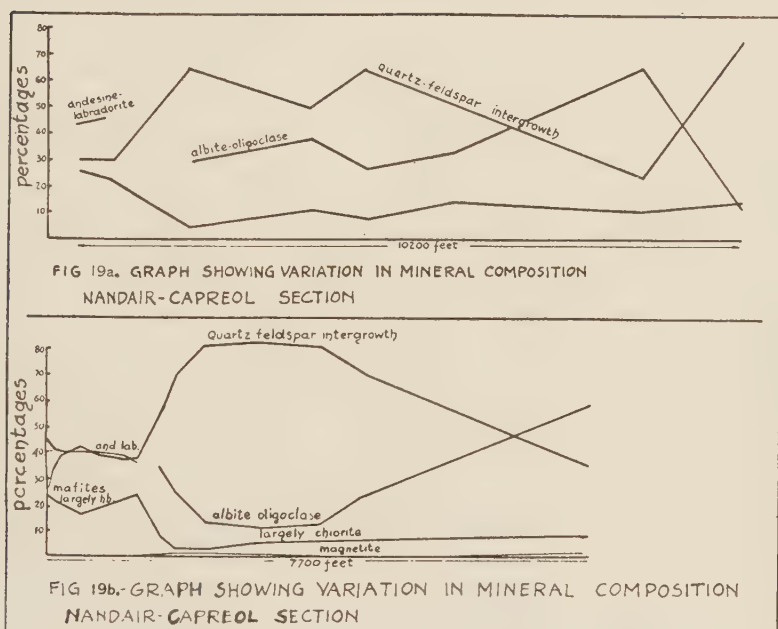


Figure 19. Variation in Mineral Composition.

rock. Beyond this is micropegmatite containing albite-oligoclase up to 55%, quartz-feldspar intergrowths up to 60%, and mafic minerals up to 20%.

The composition of the norite, considered across its whole width shows variation from place to place around the basin. Thus, the norite north of Cameron Creek fault, and again along the Capreol-Nandaïr traverse in the Northern range, has a lower percentage of plagioclase than the rock in the Southern range. The crystals are zoned, and, although the central parts are only slightly lower in anorthite proportion than in the norite of the Southern range, in total composition they are probably considerably lower. Quartz-

feldspar intergrowths make up about 30% of this more acid norite ; in the Southern range they are in much smaller amount, often being represented by low percentages of quartz. Mafic minerals are in smaller amount than in the norite of the Southern range. Along with this variation in composition is a variation in the relative width of norite outcrop to total outcrop of the Eruptive. The acid norite

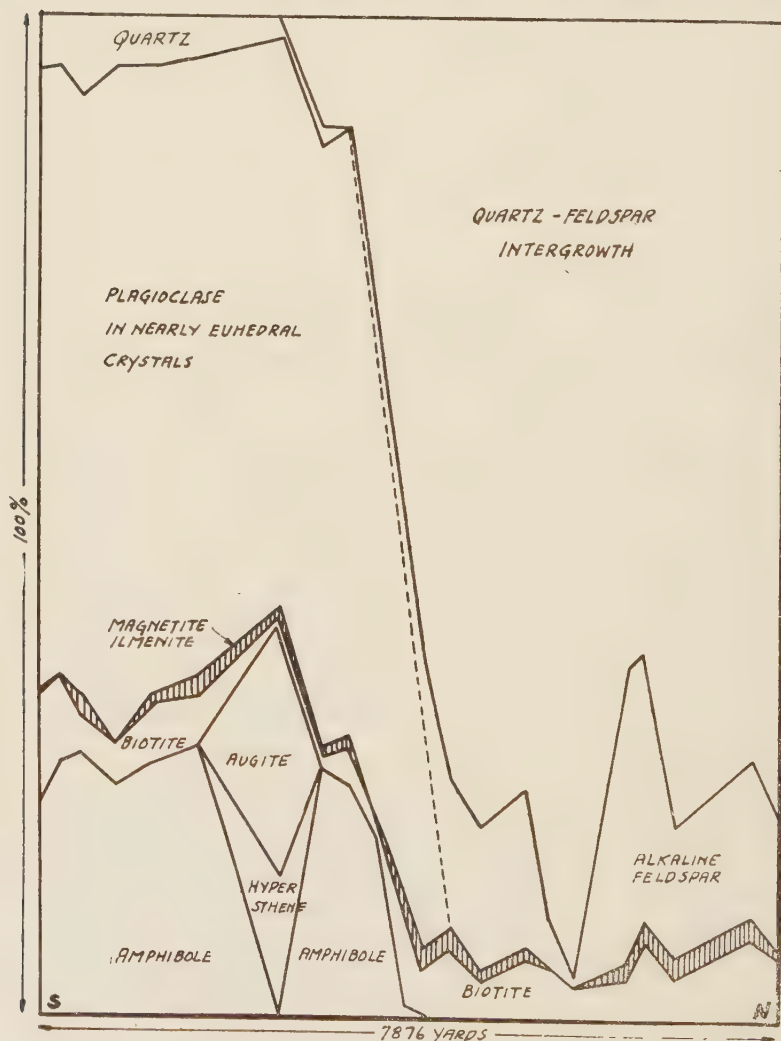


Figure 20. Mineral Composition of Nickel Eruptive Along Levack Section.

in the Nandair-Capreol section, and north of Cameron Creek fault, is about one-fifth of the total outcrop of the Eruptive. Along the Southern range the more basic norite makes up more nearly one-half of the total width.

The norite near, and at, its outer contact, which in general is rather poorly exposed, was found to be modified at many places. The outer modification is not sharply marked off from the usual more uniform norite. Near the Blezard mine, it is less than 500 feet

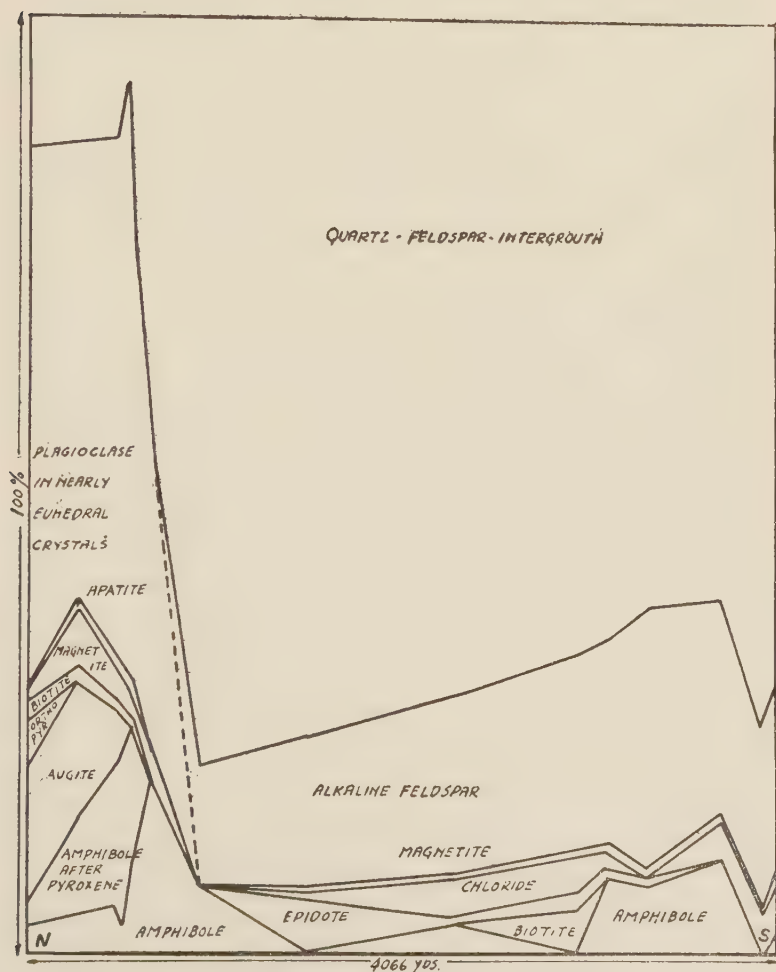


Figure 21. Mineral Composition of Nickel Eruptive Along Creighton Section.

wide. The modification is not uniform around the Eruptive. In the Southern range, as shown particularly near the Blezard mine, it differs from the norite farther inwards by being of fine-grain size, richer in quartz and biotite, and by the plagioclase crystals being zoned to a greater extent, and more sodic in total composition. The early formed minerals, particularly plagioclase, are more altered and replaced by late forming ones, as amphibole and biotite. In other parts of the Eruptive, as near Fairbank lake, and in Trill and Drury townships, the modification shows a higher percentage of plagioclase than farther inwards, but varies in composition. The norite matrix of a breccia near Chicago mine, contains 20% quartz, whereas one in Trill contains 5%. In the former place the rock is not finer grained than farther inwards, while in the latter it is. A character which appeared to be general is the smaller amount of alkaline feldspar intergrown with quartz. The modified norite has similarities to the rock of the offset dikes, which are described elsewhere.

Characteristics distinguishing the rock of the transition zone from norite are, complete alteration of plagioclase into epidote, albite, quartz, and, to a minor extent, white mica, the plagioclase represented by these pseudomorphs being in lower percentage than in the norite, and quartz-feldspar intergrowths in higher percentage. It is distinguished from micropegmatite principally in that the plagioclase of the latter is albite, or acid oligoclase, and is altered only to a minor extent. It is possible that the alteration of the plagioclase in the transition zone in which the alteration products are contained in the crystals may be represented by epidote blebs, associated with quartz, in the micropegmatite near the zone. Transition rock with unaltered plagioclase was not found. This alteration appeared to be proportional to the large amount of quartz-feldspar intergrowths present. The same general relation was seen in norite. Where the percentage of intergrowths is high, say up to 30%, alteration is marked, although in such norite white mica is more abundant than in the transition zone rock. Phemister,⁸ speaking of the norite-micropegmatite contact states that, "in the 'norite' near the micropegmatite the plagioclase has been completely altered to epidote and white mica. There has also been an introduction of quartz and to a minor extent alkali feldspar. This is quite dis-

⁸ *Loc. cit.*, p. 20.

tinct from the micrographic intergrowth of quartz and alkali feldspar which is present in the upper part of the 'norite,' and represents differentiation in the latter." The writer found only small amounts of white mica in the altered plagioclase of the transition rock. In some places a quartz-albite intergrowth occurs in the plagioclase crystals and it is believed to have been formed by alteration. The micrographic intergrowth surrounding the crystals appeared to be essentially similar to that in the norite and micropegmatite. Transition rock makes up only a small part of the whole width of the Eruptive. Most of the gradation appears to take place in two hundred yards.

Variations in the micropegmatite around the basin, comparable to those in the norite, were not observed. In places there is a large proportion of albite-oligoclase crystals, with a smaller amount of quartz-feldspar intergrowths. If the types of norite from different parts of the Eruptive are considered, a series trending toward the composition of micropegmatite is obtained. As the norite approaches the composition of the micropegmatite, alteration becomes more marked until, in the transition zone, the typical norite minerals are transformed, not into minerals similar to those in micropegmatite, but metamorphic ones, such as epidote, albite, quartz and white mica.

Marked transformation of minerals is a characteristic but variable feature of the Nickel Eruptive. Shearing and compressive stresses have affected norite and micropegmatite after solidification, particularly in the southwestern part of the basin, but changes produced through these agencies are not considered here. Phemister has ascribed part of the alteration to the contact action of the micropegmatite on the norite, following his theory of separate intrusion of these rocks. Dresser,⁹ Colony,¹⁰ Wandke & Hoffman,¹¹ and Phemister,¹² have called attention to the alterations which have gone on while the magma was solidifying, particularly during the later part of this long time-interval.

Alteration of the plagioclase in the Eruptive is of two kinds; first, alteration by the formation of such minerals as albite, epidote, quartz, and white mica; and second, replacement by mafic minerals, such as amphibole, chlorite and biotite. In places quartz penetrates

⁹ Economic Geology, Vol. XII, p. 57, 1917.

¹⁰ Journal of Geology, Vol. XXXI, p. 173, 1923.

¹¹ Economic Geology, Vol. XIX, p. 176, 1924.

¹² Trans. Roy. Soc. Canada, (3), Vol. XXII, 1928.

plagioclase and forms in it an irregular intergrowth with albite. In different places in the Eruptive plagioclase may be found in stages from quite fresh to completely altered. The plagioclase of the norite, in Trill and Drury townships, north of the Cameron Creek fault, and again in the Capreol-Nandair section, is extensively and similarly altered across its whole width. The plagioclase in the central part of the broad band of norite in the Southern range is nearly fresh, as for instance about 500 feet from the outer contact at Blezard mine. Here, as the outer contact is approached, alteration to white mica and epidote is insignificant, but replacement by biotite and amphibole increases in importance until, at the contact, a large part of the plagioclase has disappeared. Plagioclase in the micropegmatite is much less altered than in the norite.

The relation between the extent, position and nature of the alteration in the Eruptive, and the position and nature of the two parts, norite and micropegmatite, is interesting. Phemister¹³ has regarded the transition zone as resulting from a kind of contact action of fluid micropegmatite magma on solidified norite, while the latter may have been still hot. This is in accordance with his view that the norite and micropegmatite are two intrusions. To the present writer, the alteration in the transition zone is of the same character, but more pronounced than in other parts of the Eruptive. The extent of alteration to epidote, albite, quartz and white mica, the amount of zoning in the plagioclase (except in the modification near the outer contact) and the amount of micrographically intergrown alkaline feldspar and quartz vary directly throughout the norite. In the transition zone plagioclase is completely altered, and intergrowth makes up a high percentage of the rock. In the micropegmatite the plagioclase is albite, or slightly more calcic, and in it alteration has not taken place extensively. In the norite near, and at, the outer contact alteration to white mica, epidote, albite and quartz is slight, and here the matrix of the plagioclase crystals is not micrographically intergrown quartz-feldspar, but quartz for the most part. This high percentage of quartz may possibly be related to the extensive alteration to mafic minerals which occurs there.

Are the norite and micropegmatite two separate intrusions, or are

¹³ Ontario Dept. of Mines, Vol. XXXIV, Pt. 8, p. 25, 1925.

they due to differentiation, *in situ*? That they have a close genetic relation appears certain from the geographical position of the two rocks and certain similarities in their mineralogical and chemical compositions. The present writer considers differentiation, *in situ*, the theory first advanced by Doctor Walker,¹⁴ a better explanation of the relations than regarding norite and micropegmatite as separate intrusions, as has been done by Phemister.¹⁵ In the following pages some points raised by Phemister will be considered.

The space relations of the norite and the micropegmatite are instructive. In lot 9, Con. I, Trill township, micropegmatite is adjacent to rocks lying outside of the Eruptive. Phemister¹⁶ thought the micropegmatite had been forced into its present position separately from the norite, but the apparent absence of norite between micropegmatite and outer rocks is clearly due to the Cameron Creek fault.

Assuming for the moment the correctness of the hypothesis that the norite and micropegmatite were intruded separately, the norite preceding the micropegmatite, at an early stage the norite magma would solidify at both top and bottom with a fluid central part containing perhaps suspended crystals. If the micropegmatite were intruded at this stage it is reasonable to suppose that its easiest path would be along this fluid middle part, displacing, or mixing, with it as a composite sill. Such an arrangement of norite and micropegmatite is not found in the field. Considering next the micropegmatite intruded after complete solidification of the norite, as has been postulated by Phemister, one might expect the magma to intrude either at the top or bottom contact of the norite, these being surfaces of structural weakness. The non-occurrence of micropegmatite other than overlying the norite is negative evidence in favor of differentiation *in situ*. Either the micropegmatite magma was intruded exactly along the norite-overlying rock contact, or else any norite separated from the main body must be so metamorphosed as to be unrecognizable, since none is found above the micropegmatite.

The occurrence of micropegmatite overlying norite completely around the basin is strongly suggestive of differentiation *in situ*; it

¹⁴ Quart. Jour. Geol. Soc. London, Vol. LIII, p. 40, 1897.

¹⁵ *Loc. cit.*

¹⁶ *Loc. cit.*, p. 26.

accords with processes of early formed and heavy crystals moving under the influence of gravity, perhaps modified by other agencies to the outer and lower parts of the Eruptive.

As to the gradation in composition across the Eruptive, Phemister has shown that the norite (in places variable across its width) is separated by a narrow transition zone from more or less uniform micropegmatite. Coleman, Moore & Walker¹⁷ state: "It is plain from the analyses that there is a fairly rapid transition between the two facies of the Eruptive, but the microscopic method indicated that it is many times more rapid than do the chemical analyses." The lack of uniform gradation in kind and amount of minerals across the Eruptive does not in itself prove that the norite and micropegmatite are separate intrusions.

Regarding the nature of the transition zone the present writer does not agree with Phemister that its characteristics suggest a hybrid rock, formed by the action of fluid micropegmatite on solid (perhaps hot) norite. If a hybrid rock, the altered plagioclase crystals were presumably once fresh ones of the original upper contact of the norite. The material of the micrographic intergrowth would then be introduced from the micropegmatite magma, but the evidence of introduction of this material, presumably replacing the original material between the plagioclase crystals is slight. It is true that quartz-albite intergrowths extend into the highly altered plagioclase crystals, but not to a greater extent than in the norite or the micropegmatite. An unaltered alkali feldspar border to the altered crystals is frequently found in continuity with the alkali feldspar of the intergrowths. The writer did not notice any essential difference in the micrographic intergrowth of the transition zone and that of the micropegmatite, or norite. To the writer it seems probable that the transition zone contained, during solidification, plagioclase crystals in a matrix perhaps partly crystallized to quartz alkaline feldspar intergrowths, and these crystals were altered by agencies such as volatile constituents which were not present in sufficient amounts to cause such extreme alteration where and when the plagioclase crystals of the underlying norite were forming.

If the norite were intruded as a separate body it must have differentiated to give a top part intermediate between it and mi-

¹⁷ *Loc. cit.*, p. 37.

cropegmatite in composition. But one might expect it would have, on this hypothesis, a top somewhat similar to the base in composition.

Concerning different widths and nature of the norite around the Eruptive, Phemister¹⁸ states: "It is important to note that the micropegmatite is much more uniform in thickness than is the 'norite.' The 'norite' varies, in width of outcrop, from almost nothing up to two and a half miles." Where norite is narrow in outcrop, as it is along much of the eastern, northern, and western sides of the Basin, it is more acid. Where it is wide, as along the Southern range, it contains a higher proportion of first-formed minerals. The differentiation *in situ* hypothesis does not necessitate a layer of norite of uniform thickness and composition at the base of the Eruptive. Possibly the nature and amount of norite in any part of the Eruptive would be conditioned by the size of the gathering ground from which the first-formed minerals, as basic plagioclase and pyroxene, constituting the essential part of the norite, were collected. The vertical thickness of the Eruptive, if gravity were the only agent causing collection of crystals, would be the most important dimension in determining the thickness of norite. The weight of overlying crystals, compressing underlying ones and squeezing out interstitial fluid would affect the nature of the norite, making it more basic where in larger amount. Evidence of movements during solidification of the Eruptive, as oriented and fractured crystals, in an unfractured matrix, is found in the Southern range, as mentioned by Dresser¹⁹ and by Dickson.²⁰ In other parts of the Eruptive, as the Nandair-Capreol section, and the southwestern part of the basin, evidence of such movements is unimportant or absent. Phemister on the basis of separate intrusions of norite and micropegmatite suggests inhomogeneity in the original norite magma, to explain the difference in the nature of the norite around the basin. In this case the relation, that where it is narrow in outcrop it is more acid would be purely fortuitous.

In regard to the relative amounts of norite and micropegmatite, it is known that quartz-feldspar intergrowths are found in many diabases in small amount. In the Nickel Eruptive, the micropegmatite, which may be compared with the interstitial intergrowths

¹⁸ *Loc. cit.*, p. 26.

¹⁹ *Loc. cit.*, p. 566.

²⁰ Trans. American Inst. Min. Eng., Vol. XXXIV, p. 45, 1904.

in diabase, occurs in apparently greater amount, to judge from surface outcrops, than norite. Thus, if the areal proportion of the two rocks be considered as indicative of the volume proportions, the original magma from which they separated must have been quite acid. The average composition of the plagioclase occurring in more or less euhedral crystals in both norite and micropegmatite rock must be well towards the albite end. From such a magma it is difficult to find a plausible process by which unzoned labradorite crystals could be accumulated to compose about 70% of a differentiate, as they do in the norite of places in the Southern range.

Daly²¹ has pointed out, "that the outcrop areas of the rocks cannot be assumed to show the exact ratio of volumes between acid and basic types in this sheet." The shape of the Nickel Eruptive is so largely unknown that the possibility of norite constituting a much larger proportion than shown on surface seems reasonable enough. In another place the writer has attempted to show, by a variation diagram how two rocks with the chemical compositions of norite and micropegmatite might form from a parent magma. If the assumptions made there regarding the composition of the parent magma are correct, a larger amount of norite than micropegmatite is implicitly indicated on the diagram. Bowen²² has suggested deformation after partial crystallization as a possible means of giving this apparent excess of acid differentiate. The present writer did not find evidence of extensive disturbance taking place while the Eruptive was partially crystallized. Bain²³ has attempted to explain this apparent excess as arising through assimilation of very large amounts of Huronian sediments, but this has not been proved.

In the variation in the norite, as Phemister points out,²⁴ the most basic part of the norite is about one-half to three-quarters of the norite's width from the basal contact. This may be considered true only for parts of the Eruptive, as along the Southern range. In other parts the norite is essentially uniform. The locus of maximum accumulation of first-formed crystals would presumably be not at the very base, but some distance above it, possibly conditioned by the rate of solidification.

²¹ *Igneous Rocks and Their Origin*, p. 348, 1914.

²² *Journal of Geology*, Vol. XXIII, p. 825, 1925.

²³ *Journal of Geology*, Vol. XXIII, p. 509, 1925.

²⁴ *Loc. cit.*, p. 25.

Phemister²⁵ gives, as evidence in favor of two intrusions, the greatly altered condition of the norite near its transition zone into micropegmatite, ascribing the alteration to a kind of contact action of the micropegmatite magma on solid norite. The present writer has attempted to show in an earlier part of this article that the alteration in the norite appears to bear a more definite relation to the amount of quartz-feldspar intergrowths contained than to its proximity to the micropegmatite.

In lot 5, Con. 1, Trill township, a dike-like body of rock resembling micropegmatite cuts across the transition-zone rock. Phemister²⁶ records a vein of quartz-rich micropegmatite, about a foot wide, cutting norite north of Creighton mine. While such occurrences suggest the micropegmatite is a separate intrusion, it is also possible that movements during solidification of the Eruptive might force fluid micropegmatite magma into parts of the Eruptive which had already solidified.

If the Eruptive were one intrusive differentiated *in situ*, it might be supposed that at top and bottom, the magma would be chilled, giving contact phases which would tend to approximate the composition of the original magma. The upper micropegmatite contact is not similar to the lower norite contact and the latter is not constant around the basin. All the minerals in the outer norite contact rock are not fine-grained, quartz particularly, occurring in large crystals. From the nature of the metamorphism in the rocks outside the norite, *e.g.*, the formation of sudburite, indicating very high temperatures, and the lack of a truly fine-grained phase in the norite near, and at, its contact, it appears unjustified to regard the contact-rock as more than tending to approximate the composition of the original magma. It is more acidic than the main part of the norite.

It does not seem possible, in the present state of knowledge of the Nickel Eruptive, to state the exact processes by which norite and micropegmatite formed in the Eruptive. In a separate paper on the "offset dikes" of the Nickel intrusive, the writer has attempted to show the compositions of two rocks resulting from the migration of plagioclase and pyroxene crystals from one part of a magma to another, give the composition of the original magma.

²⁵ *Ibid.*, p. 25.

²⁶ *Loc. cit.*, p. 20.

The theoretical compositions of the rocks are thus compared with the actual compositions of norite and micropegmatite as shown by numerous analyses. In the writer's opinion the theoretical and actual compositions are sufficiently close to suggest that this process of crystal differentiation has operated to some extent.

From the consideration given above it is concluded that differentiation *in situ* is a more reasonable explanation of the relations of norite and micropegmatite than separate intrusions.

During parts of the years 1927 and 1928, the writer, under Dr. W. H. Collins of the Geological Survey of Canada, assisted in mapping the southwestern part of Sudbury basin. Specimens were examined at the University of Chicago and the writer is indebted to Doctor Johannsen and Doctor Bastin for suggestions and criticisms. Dr. T. L. Walker kindly allowed the writer permission to examine material at the University of Toronto.

THE 'OFFSET DIKES' OF THE NICKEL INTRUSIVE, SUDBURY, ONTARIO.

ROBERT THOMSON.

Published with the permission of the Director, Geological Survey of Canada, Department of Mines, Ottawa, but without concurrence in all the opinions expressed.

ABSTRACT.

Four dikes in the vicinity of the Nickel Intrusive, Sudbury, Ontario, were described by Coleman under the name 'offset dikes.' Coleman believed them to be genetically related to the Intrusive, more closely to the norite of the Intrusive. In the present article some of these dikes are described, and the hypothesis is advanced that they approximate the composition of the parent magma from which the norite and the granophyre ("micropegmatite") of the Intrusive originated. An attempt is made to show how two rocks with the chemical compositions of norite and micropegmatite, as these names are applied at Sudbury, might form from a magma of the chemical composition of the offset dikes.

INTRODUCTION.

Four dikes, called 'offset dikes,' in the vicinity of the Nickel Intrusive, Sudbury, Ontario, have been mapped and described by Coleman.¹ They are currently referred to as the Frood-Stobie, Copper Cliff, Worthington, and Foy offsets. Coleman believed these dikes genetically related to the Intrusive, more specifically to be mixtures of norite and ore that had been injected from the Intrusive (after emplacement) into the surrounding rocks. Other writers, as Knight² and Phemister, who do not accept as a possible explanation of the sulphide ore deposits the theory that the ores are differentiates in situ of the Intrusive, place little emphasis on the question of the relation of the dikes to the Intrusive.

Of the four dikes mapped by Coleman, the writer examined the Worthington only. From the similarity of one thin section from a dike called 'younger norite' at Creighton mine to the rock from the offset dikes, the younger norite is suggested to be an offset dike also.

WORTHINGTON DIKE.

Worthington dike extends four miles in a southwesterly direction passing through the village of Worthington. South-

¹ Coleman, A. P.: *The Nickel Industry*, Canada Department of Mines Branch, 1913.

² Knight, C. W.: Royal Ontario Nickel Commission, pp. 105-209, 1917; Phemister, T. C.: Ontario Department of Mines, vol. XXXIV, pt. VIII, pp. 30-32, 1925.

west of Worthington mine, the dike, here about 120 feet wide, shows differences across its width. On each side of the dike is a zone some twenty feet wide of massive gray-green fine-grained rock with only sporadic boulders of graywacke, which is the surrounding country rock at this place. The central part of the dike, eighty feet in width, consists of boulders of amphibole in a matrix that is similar to the rock in the outer parts of the dike. This arrangement, a central inclusion-rich zone surrounded by an intrusive-free, or almost free, zone, is characteristic of the dike throughout its length. Coleman, Miller and Knight, Wandke and Hoffman,³ and Phemister write of movements—shearing, crushing, brecciation—along the dike. The writer found no evidence of this. The included fragments of the central breccia are different from their matrix. They can be matched from nearby rocks along the dike and have been carried into their present position, and were not formed there by brecciation of dike rock. The matrix of the breccia is not sheared nor is the rock of the outer zones of the dike. No important stratigraphic displacement of the sedimentary rocks or altered diabase bodies intersected by the dike was found.

The breccia zone in the central part of the dike is interesting. Its occurrence in that place combined with the practical absence of inclusions in the outer zones suggests two stages in the formation of the dike. Large included boulders are of different rock from that of the dike walls at many places, showing that the boulders have moved some distance to their present positions.

Rock description.—The dike rock is fine grained, rather fresh in appearance, dark gray, and shows biotite and blue quartz. These two minerals give it an appearance similar to the norite of the Nickel Intrusive at its outer contact. The results of a Rosiwal analysis (in volume percentages) are shown in Table I. Zoning in the plagioclase (of composition about Ab_1An_1 in the central parts of the crystals) is marked. Alteration to epidote, white mica, and carbonate occurs to a small extent. Intergrowths of quartz and feldspar occur in

³ Coleman, A. P.: The Sudbury nickel field; Ontario Bureau of Mines, vol. XIV, pt. III, pp. 30 and 114, 1905.

———: The Nickel Industry; Canada Dept. of Mines, Mines Branch, p. 46, 1913.

Miller, W. G., and Knight, C. W.: Nickel Deposits of the World, p. 174.
Wandke, A., and Hoffman, R.: The Sudbury nickel deposits; Econ. Geol., vol. XIX, p. 195, 1924.

small amount. The feldspar crystals are frequently enclosed in a matrix of quartz, which is optically continuous over small areas. No pyroxene was seen, and it was uncertain if any of the amphibole was secondary after pyroxene. Biotite and amphibole are intimately associated. The deep-brown biotite, in many places chloritized, frequently encloses irregular masses of magnetite with leucoxene and apatite. Sulphides, occurring as small blebs and larger masses throughout the dike, have textural relations indicating replacement of the silicates.

Dikes near Ethel Lake.—Two small dikes near Ethel Lake, lot 7, Con. IV, Denison township, are lithologically similar to the Worthington dike and may be merely extensions of it. An average of the estimated mineral composition of four thin sections is shown in Table I.

TABLE I.

Mineral Composition in Volume Percentages of Worthington Dike, Two Dikes near Ethel Lake, and the 'Younger Norite' Dike at Creighton Mine.

	Worthington dike	Ethel Lake dikes	'Younger norite' dike
Andesine	27%	52%	33%
Amphibole	32	21	30
Biotite + accessories	24	10	12
Quartz	17	17	25

'YOUNGER NORITE' DIKE AT CREIGHTON MINE.

A dike intruding the norite at its outer contact at Creighton mine has been described by the International Nickel Co's.⁴ staff. The rather unaltered dike is stated to intrude the rocks outside the norite, notably the Creighton granite, which is usually regarded as younger than the norite.

The present writer obtained a specimen of the 'younger norite' dike from the twentieth level, through the Mine Manager of Creighton mine. No further examination, other than on the thin section from this specimen, was made. A Rosiwal analysis gave the results (in volume percentages) shown in Table I. The minerals and the nature and extent of their alteration are similar to those in the Worthington dike.

⁴ International Nickel Co's. staff, The Mining and Smelting Operations of the International Nickel Co. of Canada: Trans. Canadian Inst. of Min. and Met., p. 23, 1920.

REMARKS.

That these dikes are closely related to each other is strongly suggested by their lithological similarity, i.e., the kind and relative amount of their component minerals (although this varies somewhat widely as shown in Table I) and their texture. The writer found no other dikes resembling them near Sudbury. A point suggesting a community of origin is the very common occurrence of sulphides in association with them. The rather common occurrence of igneous breccias with them may also be significant. Little information regarding their age, particularly their relation to the Nickel Intrusive and the granites younger than the Intrusive, and whether they were intruded contemporaneously or not, is at hand. They are clearly younger than the sediments and altered diabase sills and masses south of the Intrusive. Further, they were intruded after these sills had been altered to amphibolite, as is shown by the occurrence of the altered diabase (amphibolite) as boulders in the Worthington dike. Certain evidence on the relation of the offset dikes to the Intrusive is conditional on the correctness of the writer's grouping of the 'younger norite' (which cuts through norite) with them. This is done from the slight evidence of one thin section only.

The rock of the dikes shows similarities to the norite of the Nickel Intrusive. Both the dike rock and the norite have variation in mineral composition. The usual dike rock is much more acid than most of the norite, but there are varieties that resemble the usual type. That part of the norite which most closely resembles the dikes is near its outer contact, particularly near Blezard mine. This markedly acid modification at its outer contact is not constant around the basin, although in several places the writer noted a trend in that direction. The acid norite and the usual dike rock are similar in the following respects: The plagioclase of both is about Ab_1An_1 in composition in the central part of the crystals and both are strongly zoned outwards. Pyroxene is absent, the important mafic minerals being amphibole and biotite. It seems probable that most of the amphibole is primary. Quartz is abundant in both. Another point of similarity, rather striking in thin sections, is the textural relation of the quartz to the other minerals, particularly plagioclase. These, particularly the plagioclase, are poikilitically included in the quartz, which extinguishes simultaneously over rather large areas under crossed nicols. Very

little quartz-feldspar intergrowth, so characteristic of the micropegmatite and a large part of the norite, occurs. Other considerations suggesting a relation to the Intrusive is the general proximity of the dikes to it, and the rather constant association of sulphide ore deposits with both. This has been stressed by Coleman in numerous publications.

The intermediate mineral composition of the dikes, between norite and granophyre ("micropegmatite"), is shown by the following considerations: Quartz is in much higher percentages in the dikes than in the usual norite. Plagioclase is in smaller percentage than in the usual norite. While the composition of the central parts of the crystals is approximately the same in both norite and dikes, zoning is more marked in the dikes, making them more sodic in total composition. Mafic minerals are in as high or higher percentages than in most of the norite, but it is noteworthy that they are later crystallizing minerals—amphibole and particularly biotite—as contrasted with pyroxene.

From these considerations the writer concludes that the dikes are intermediate between norite and micropegmatite and regards the similarity between the usual dike rock and the modification of the norite near its outer contact, particularly as seen at Blezard mine, to be significant.

CHEMICAL COMPOSITION OF THE DIKES.

Some chemical analyses (Table II—cols. 7, 8, 9, 10) were available to the writer. They suggest a similarity between the dikes and the norite, but they are far from uniform. Mr. Rickaby, of the Ontario Department of Mines, kindly placed at the writer's disposal some chemical data dealing with the questions that the writer had investigated by thin sections. Mr. Rickaby had had analyses made of these offset dikes at various places. These are published here for the first time (Table I, cols. 1 to 4). Next he compared these analyses with the average of the 48 analyses given by Coleman, Moore, and Walker,⁵ taken at regular intervals along certain sections of the Nickel Intrusive. This average is given in column 5, Table II. It is quite similar to columns 1 to 4, as may be seen by inspection. That this similarity is merely fortuitous seems

⁵ Coleman, A. P., Moore, E. S., and Walker, T. L.: The Sudbury Nickel Intrusive; Analyses Nos. 37-74 and 82-92: Contributions to Canadian Mineralogy No. 28. University of Toronto studies, 1929.

highly improbable. If the norite-micropegmatite average is to be taken as the composition of the parent body from which norite and micropegmatite differentiated, certain assumptions must be made. One is that the analyses cover every variety of norite and micropegmatite whether exposed at the present surface or not. Another is that each analysis is representative of an equal volume of rock.

The present writer here attempts to test and extend Rickaby's results. The other analyses of the dikes (Table II, cols. 7 to 10) are neglected since they depart from the nearly uniform analyses of Rickaby.

VARIATION DIAGRAM OF THE NICKEL INTRUSIVE.

To compare the composition of the offset dikes with that of the Intrusive, the writer prepared a variation diagram of the latter. This is shown in Fig. 1. The silica percentages are plotted along the axis of abscissas and the percentages of the most important oxides, other than silica, along ordinates. The diagram was prepared from 97 analyses of norite and micropegmatite, taken from Walker; Coleman, Moore, and Walker; Knight; and Coleman.⁶ Norite lies on the left-hand side of the diagram at lower silica percentages than micropegmatite. A marked scattering of the points on the diagram is noteworthy.

The composition of the offset dikes (the average of Rickaby's analyses, Table II, col. 6) is shown by the crosses along the ordinate arising from silica percentage 59.5. Its intermediate relation to norite and micropegmatite is brought out, without bringing into account the relative amounts of norite and micropegmatite.

THEORETICAL DERIVATION OF NORITE AND MICROPEGMATITE FROM MAGMA WITH COMPOSITION OF OFFSET DIKES.

A plausible theory advocated among others by Bowen, to explain the origin of norite and micropegmatite from a parent magma is that the first formed crystals, plagioclase and pyroxene,

⁶ Walker, T. L.: *Quart. Jour. Geol. Soc.*, vol. 53, p. 56, 1897.

Coleman, A. P., Moore, E. S., and Walter, T. L.: *op. cit.*

Knight, C. W.: *Econ. Geol.*, vol. 18, pp. 592-594, 1923.

—: Royal Ontario Nickel Commission, pp. 117-119, 1917.

Coleman, A. P.: Ontario Bureau of Mines, p. 212, 1904.



Fig. 1. Variation diagram for the Nickel Intrusive. Analyses of norite and micropegmatite are represented by circles. The average composition of the offset dikes are indicated by crosses along silica percentage 59.5. The composition of a mixture of calcic plagioclase, orthorhombic and monoclinic pyroxenes is shown by squares along silica percentage 51.5.

TABLE II.
Analyses Relating to Offset Dikes.

	(1)	(2)	(3)	(4)	(5)
SiO ₂	59.76	60.12	60.15	57.90	61.23
TiO ₂	0.84	0.83	1.03	0.93	0.90
Al ₂ O ₃	15.65	16.63	15.23	17.57	14.69
Fe ₂ O ₃	1.90	1.04	1.46	1.78	1.68
FeO	5.96	5.65	7.07	5.89	5.81
CaO	5.90	5.46	5.35	3.81	4.99
MgO	4.05	4.06	3.33	4.29	3.58
Na ₂ O	2.90	2.06	2.30	2.90	3.05
K ₂ O	1.88	2.54	2.36	3.40	2.62
H ₂ O	1.04	1.51	1.03	1.35	1.30
CO ₂	nil.	.03	.31	.09	.14
MnO	.10	.10	.08	.07	.10
P ₂ O ₅	.21	.16	.18	.11	.34
S	.19	.16	.46	.27	.08
	100.38	100.35	100.34	100.35	100.51
	(6)	(7)	(8)	(9)	(10)
SiO ₂	59.48	57.98	51.20	57.40	54.90
TiO ₂	0.91	....	....	....	....
Al ₂ O ₃	16.27	18.94	17.32	15.61	19.02
Fe ₂ O ₃	1.54	2.24	5.04	....	5.00
FeO	6.14	6.93	9.06	10.02	8.51
CaO	5.13	5.71	6.76	5.45	5.90
MgO	3.93	1.84	4.14	4.49	1.68
Na ₂ O	2.54	2.01	2.32	....	1.99
K ₂ O	2.54	2.45	2.14	....	1.72
H ₂ O	1.23	.98	2.15	....	tr.
CO ₂	.11	.52	.25	....	1.81
MnO	.09	....	....	....	....
P ₂ O ₅	.16	....	....	....	....
S	.27	....	....	....	....
	100.34	99.60	100.38	....	100.53

Col. 1. Frood-Stobie offset; from point 500 feet west of Stobie pit. Analysis furnished by H. C. Rickaby.

Col. 2. Copper Cliff offset; west of Lady MacDonald Lake. Analysis furnished by H. C. Rickaby.⁷

Col. 3. Worthington offset; near Totten mine. Analysis furnished by H. C. Rickaby.

Col. 4. Foy offset; near Hollow lake. Analysis furnished by H. C. Rickaby.

Col. 5. Average of 48 analyses of norite and micropegmatite (given by Coleman, Moore, and Walker—*op. cit.*). Average by Burrows and Rickaby.

Col. 6. Average of cols. 1, 2, 3, and 4.

Col. 7. Worthington offset, Totten mine. Royal Ontario Nickel Commission, p. 176, 1917.

Col. 8. Offset dike at Evans mine. Royal Ontario Nickel Commission, p. 119, 1917.

Col. 9. Worthington offset at Worthington mine. Royal Ontario Nickel Commission, p. 176.

Col. 10. Worthington offset. Royal Ontario Nickel Commission, p. 176, 1917.

⁷ Burrows, A. G., and Rickaby, H. C.: Sudbury Basin Area; Ontario Department of Mines, vol. 38, pt. III, p. 27, 1929.

migrated from one part of the parent magma to another during consolidation. Micropegmatite thus represents the parent magma minus crystals, and norite the parent magma plus crystals. For present purposes no assumption need be made whether the crystals dissolved prior to final solidification or not, and indeed whether differentiation took place in situ or not.

If the composition of a parent magma and the composition of a substance or substances (e.g., crystals) that migrate from one part of the magma to another be known, the final composition of all parts can be ascertained from a variation diagram. The assumption is made that no material has been assimilated and that no material from the magma has migrated into the bordering rocks. If the further assumption be made that the substance that migrated (either one kind of crystal or several) always retains a constant composition, the lines showing the possible variation in composition, caused by the substance being subtracted in varying amounts from one part of the parent magma and added in varying amounts to other parts will be straight lines. The straight lines are defined by two points for each oxide considered; one point is given by the percentage of that oxide in the parent magma, the other by the percentage of the same oxide in the migrating crystal.

This has been done for the more important oxides in Fig. 1. For the composition of the parent magma the average of Rickaby's analyses of the offset dikes is used. For the composition of the migrating material, the writer found the composition of a mixture of calcic plagioclase, orthorhombic pyroxene, and monoclinic pyroxene. This seems reasonable, since these are early crystallizing minerals, occur in the norite and not in the micropegmatite, and further they are the only important early-crystallizing minerals (olivine is absent in the Intrusive, magnetite is in general not important). For the composition of the plagioclase the writer used the analysis (Table III, col. 1), given by Coleman, Moore, and Walker⁸ of plagioclase actually occurring in the Intrusive. The analysis of orthorhombic pyroxene (Table III, col. 2) from the Intrusive, given by the above-named authors was also used.⁹ For the composition of monoclinic pyroxene the writer used the analysis (made by M. F. Connor), quoted by Phemister,¹⁰ of partly uralitized

⁸ Coleman, A. P., Moore, E. S., and Walker, T. L.: *op. cit.*, p. 13, 1929.

⁹ *Op. cit.*, p. 14, 1929.

¹⁰ Phemister, T. C.: A comparison of the Keweenawan sill rocks of Sudbury and Cobalt, Ontario; *Proc. and Trans. Roy. Soc. of Canada*, sect. IV, p. 139, 1928.

augite from diabase at Gowganda. Phemister notes from optical examination that the mineral here is similar to that at Sudbury. The composition is shown in Table III, column 3. These analyses were combined graphically to find the composition of a mixture, 68.1 per cent labradorite, 31.1 per cent orthorhombic pyroxene (recalculated to 100), and 7.8 per cent augite. This particular ratio was obtained merely by trial to find lines that would agree most closely with the actual variation diagram of the Intrusive. The composition of the mixture (Table III, col. 4) is plotted along the ordinate arising

TABLE III.

Analyses Relating to Early-Forming Minerals in Nickel Intrusive.

	(1)	(2)	(3)	(4)
SiO ₂	52.52	50.55	48.00	51.5
TiO ₂	.23	.57	.91	...
Al ₂ O ₃	29.23	6.20	4.31	20.1
Fe ₂ O ₃	1.10 = (total iron)		3.06	.9
FeO	(total iron) = 16.90		17.34	6.8
MgO	.39	21.65	9.82	7.9
MnO	.01	.45	....	..
CaO	10.56	1.16	14.84	8.0
Na ₂ O	4.42	....	.91	2.8
K ₂ O	.98	....	.15	0.7
H ₂ O .....	....	....	.07	...
H ₂ O— .....	....	....	1.00	...
	99.44	97.48	100.41	...

Col. 1. Labradorite from Nickel Intrusive. Analysis given by Coleman, Moore, and Walker, *op. cit.*, p. 13.

Col. 2. Orthorhombic pyroxene from Nickel Intrusive. Analysis given by Coleman, Moore, and Walker, *op. cit.*, p. 14.

Col. 3. Partly uralitized augite from diabase at Gowganda. Analysis quoted by Phemister, *op. cit.*, p. 139.

Col. 4. Composition of a mixture 68.1 per cent (1), 31.1 per cent (2), and 7.8 per cent (3).

from silica percentage 51.5, the various percentages of the other oxides being indicated by squares.

The scattered distribution of the points in the variation diagram of the Intrusive has already been mentioned. Obviously no straight or simply curved line could pass through all the points. The most general and simple explanation of the scattering is that the migrating crystals, considered as a whole, did not maintain a constant composition, e.g., in one part of the parent magma plagioclase crystals might be extracted in a

different ratio to the pyroxenes than in another part. Possibly more important than this, the plagioclase crystals might eventually come to rest in the parent magma in such fashion that at one place they might be the predominant addition to it and in another be subordinate to pyroxenes. Another factor, which combined with the preceding, might act to produce scattering and departures from straight lines is the progressive change in the composition of any one kind of crystal, e.g., plagioclase, during solidification of the Intrusive. Assimilation of the bounding rocks (of composition different from the parent magma) without complete mixture in it would also produce this effect. A fourth cause is the non-uniform migration of substances, presumably aided by volatile agents, through parts of the Intrusive completely or nearly completely solidified during the concluding stages of consolidation of the Intrusive. Evidence for this is quite clear in thin sections. As an extreme example, the plagioclase of the rock may be completely replaced by epidote in one place while a short distance away a considerable part of it may be unaltered. By this replacement a change is caused in the chemical composition from what it was before replacement. Variations caused by such agencies show as a scattering of the points in the diagram.

The writer endeavored to draw the straight lines to pass through a maximum concentration of points in the diagram. A better agreement might possibly be obtained by using different ratios of the three kinds of crystals, or by using different compositions for the crystals. The oxides most in error are ferrous iron and magnesia, with soda and potash to a lesser extent. It may be noted that these discrepancies are in pairs and further are somewhat compensating. Thus magnesia cuts zero percentage at 67 per cent silica while ferrous iron is too high at high percentages of silica. If the material subtracted from the parent magma contained one per cent less magnesia and one per cent more ferrous iron better agreement would be obtained. Such a correction related back to the pyroxenes does not appear unjustified. Again, potash is too high at high silica percentages and soda too low. Possibly the plagioclase of the migrating crystals might contain more potash and less soda than given in the analyses used.

In the writer's opinion, the foregoing results (only an illustration of how differentiation might have gone on in the Intrusive) on the variation diagram support the hypothesis

that the offset dikes are intermediate between norite and micropegmatite, that from a magma of such composition the two rocks might be derived.

REMARKS.

A comparison between the dikes and the Intrusive must remain inconclusive until more data are obtained. Rickaby's analyses and some of the writer's thin sections bring out the intermediate nature of the dikes; other analyses (Table II, cols. 7-10) and some of the writer's sections show a strong resemblance to norite. The writer would emphasize the intermediate nature.

The writer wishes to avoid the question whether the Intrusive differentiated in situ or not in the present paper. It enters in, however, and the writer considers the evidence strongly supports the differentiation in situ hypothesis.

ACKNOWLEDGMENTS.

The dikes described were examined in the field during 1928, while the writer was acting as field assistant to Dr. W. H. Collins, Geological Survey of Canada. The thin sections were examined at the University of Chicago. The writer is indebted to Prof. A. Johannsen and Dr. T. L. Walker for reading the manuscript. He is particularly indebted to Mr. Rickaby, Provincial Geologist of Ontario, for permitting the use and publication of his analyses.

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SUDBURITE, A METAMORPHIC ROCK NEAR SUDBURY, ONTARIO¹

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ABSTRACT

"Sudburite" is the name applied to a rock composed essentially of plagioclase and pyroxene, with hornfels texture, occurring in proximity to the nickel intrusive near Sudbury, Ontario. Evidence is given to show that it is due to the recrystallization of greenstone and other rocks, older than the nickel intrusive, and that the intrusive was the cause of its formation.

INTRODUCTION

Certain rocks in the vicinity of the nickel intrusive, near Sudbury, Ontario, have been described by Coleman under a variety of names, as "micronorite,"² "older norite,"³ and "sudburite."⁴ In 1903 he described these rocks as a variety of the norite of the nickel intrusive, with reservations as to origin.⁵ Later the sudburite was stated to be a basic extrusive. The present writer encountered this sudburite in the course of field work during 1928, and afterward, through microscopic examination, concluded it to be a metamorphic rock. The most abundant minerals in sudburite are monoclinic pyroxene, orthorhombic pyroxene, and plagioclase. The texture is fine-granular. The writer believes the important processes in the formation of this rock were the recrystallization of large plagioclase crystals into fine granules, and the crystallization of pyroxene from amphibole and biotite. Where these two processes have gone to completion, typical sudburite (plagioclase-augite-hornfels) is produced. In places plagioclase has recrystallized, whereas hornblende has not, which gives rise

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² A. P. Coleman, "The Northern Nickel Range," *Ont. Bur. of Mines 13th Ann. Rept.*, Part I (1904), p. 214.

³ "The Sudbury Nickel Field," *Ont. Bur. of Mines 14th Ann. Rept.*, Part III (1905), p. 78.

⁴ "The Proterozoic of the Canadian Shield and Its Problems," *Problems of American Geology* (1913), p. 103.

⁵ *Ibid.*

to difficulty in naming this variety, since it has not all the typical features of sudburite. A further complexity is introduced in sudburite, because the pyroxene and frequently the other minerals also have been altered nearly everywhere to hornblende.

Sudburite occurrences are restricted to the vicinity of the outer margin of the intrusive. It was apparently formed from different types of rocks, but more strikingly from basic ones.

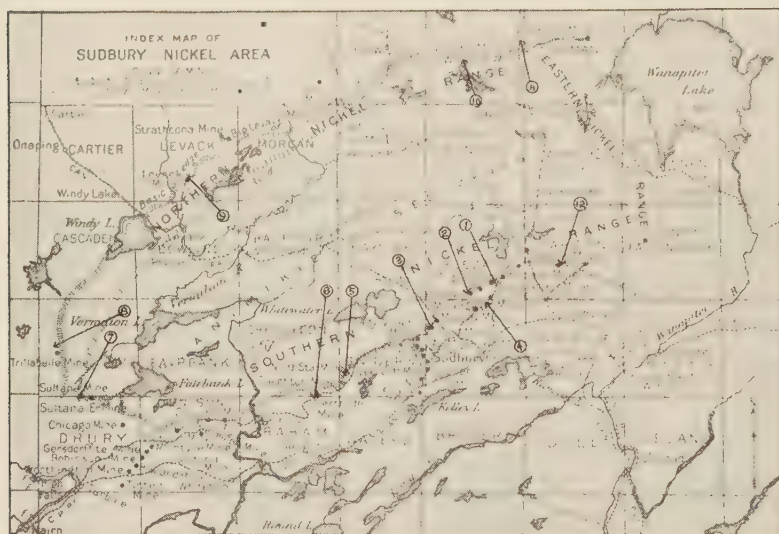


FIG. 1.—Map of the Sudbury Nickel-Copper area, Ontario, Canada, showing the location of the mines. The outlines of the norite-micropegmatite are also indicated.

OCCURRENCES AND DESCRIPTION

A sketch made of the Sudbury area shows the location of the places mentioned below (Fig. 1).

Locality 1, Blezard Township, lots 4 and 5, Concessions I and II.—On maps accompanying Coleman's reports, sudburite is shown as a somewhat elongated mass extending along the norite contact and up to about half a mile from it.

It is well exposed at the junction of the Sudbury-Capreol highway and the road leading off it to Mount Nickel mine, and again on the east side of the Sudbury-Capreol highway, south of the slag piles at Blezard mine. The fine-grained rock is traversed by raised amphi-

bole veinlets, and amphibole crystals (up to $\frac{1}{2}$ inch in diameter) with embayed outlines are found in it. Amphibolitic rocks, apparently formed by alteration of sudburite, intervene between it and the norite of the intrusive. The fine-grained sudburite grades into rocks in which the recrystallization processes, giving rise to sudburite, have not gone to completion, and also into rocks in which later alteration, largely to amphibole, has obscured its original nature. Thus, in addition to the typical fine- and even-grained variety there are others with abundant and, in many cases, large hornblende crystals. Accurate mapping of these rocks would require very detailed work.

Thin sections of fine-grained sudburite contain monoclinic pyroxene, orthorhombic pyroxene, plagioclase (between andesine and basic labradorite), and magnetite as the principal minerals. Biotite is present in small amounts. Quartz and pyrite are mentioned by Coleman⁶ as minerals occurring in very small amounts. All these minerals are unaltered. In some thin sections pyroxene and plagioclase are in about equal amounts. Orthorhombic pyroxene is often more abundant than monoclinic.

A granoblastic texture is characteristic of the rock. The granules are usually of rather uniform size (Fig. 2), but in places pyroxene granules are larger than those of plagioclase. Occasionally pyroxene granules are aggregated to form bands across the thin section. Magnetite in places shows idiomorphic outlines against the other minerals. Thin sections of large amphibole crystals contained within, and having irregular outlines against, fine-grained sudburite show pyroxene granules developed in them. The amphibole crystals are remnants of the original rock not completely altered to sudburite. In places remnants of hornblende are surrounded by pyroxene granules (Fig. 3).

Locality 2, Blezard Township, lot 8, Concession IV.—Through the courtesy of Dr. T. L. Walker, the writer had the opportunity of examining some thin sections of rocks from this locality. Chemical analyses of these rocks have been given by Coleman, Moore, and Walker⁷ in their important work on the nickel intrusive.

⁶ "The Northern Nickel Range," *op. cit.*, p. 215.

⁷ A. P. Coleman, E. S. Moore, and T. L. Walker, *The Sudbury Nickel Intrusive*, "Contributions to Canadian Mineralogy" (University of Toronto Press, 1929), pp. 28–29.

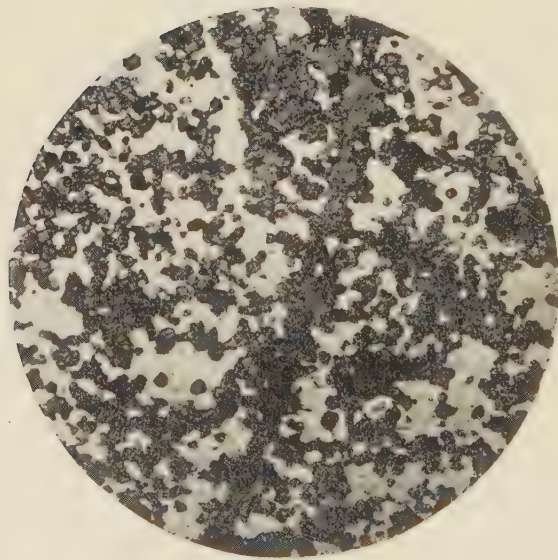


FIG. 2

FIG. 2.—Sudburite, near Blezard mine. Pyroxene and plagioclase granules. Amphibole veinlet, crossing section, alters pyroxene particularly. Ordinary light, $\times 7$.

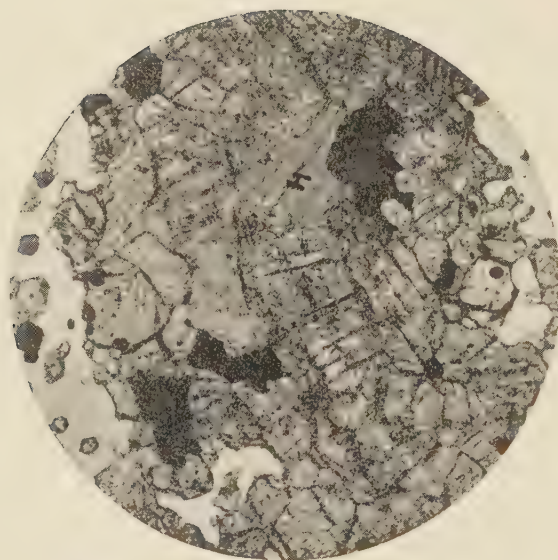


FIG. 3

FIG. 3.—Sudburite. *H* = hornblende, surrounded by pyroxene granules, which appear to have formed from it. Ordinary light, $\times 25$.

A glance at the analyses given shows that analysis No. 64 differs markedly from the rest of the series—Nos. 65, 66, etc. Under the microscope (Slide No. M-15956, Royal Ontario Museum, Toronto) the rock of this analysis proved to be sudburite.

Locality 3, McKim Township, lots 11 and 12, and adjacent areas of Snider Township, lot 1, Concessions IV and V.—This is in the vicinity of Murray mine. The writer saw typical sudburite here and also varieties with hornblende in varied amounts.

Locality 4, Frood Stobie offset.—The rock about 100 feet southeast of the shaft (formerly owned by the Mond Nickel Co.) on the offset and also that from immediately west of the open pit at Stobie mine were found, under the microscope, to be varieties of sudburite.

Locality 5, near Creighton mine.—A thin section (Slide No. M-15915, Royal Ontario Museum, Toronto) from here was identified as sudburite.

Locality 6, Creighton Township, lots 2, 3 and 4, Concession I (in the vicinity of Gertrude mine).—The sudburite here is in a quartz gabbro mass and is believed to be a metamorphosed part of it. Typical sudburite was not found in contact with norite (of the nickel intrusive) but separated by 20 yards or more. The intervening rock has been highly altered, largely to amphibole. About 300 feet west of the railway triangle in lot 3, Concession I, is a small area of sudburite.

Locality 7, near Sultana mine.—Parts of the greenstone at and near the mine are sudburite.

Locality 8, Trill Township, lot 9 (west side, south half), Concession III.—Inclusions in the granite here, as shown by thin sections, are similar to sudburite.

Locality 9, near Levack mine.—Brackenbury⁸ reports the occurrence of sudburite in this locality.

Locality 10, Wisner Township.—Coleman⁹ mentions its occurrence near Joe's Lake in this township.

Locality 11, near Nandair on the Canadian National Railway, north of the outer norite contact.—A thin section (Slide No. M-15922, Royal

⁸ C. Brackenbury, "Notes on the Rocks at Levack," *Ont. Bur. of Mines 23d Ann. Rept.*, Part I (1914).

⁹ "The Sudbury Nickel Field," *loc. cit.*, p. 81.

Ontario Museum, Toronto) labeled "greenstone cement of granite fragments" is incompletely developed sudburite. A thin section of granite showed partial recrystallization of large albite crystals into smaller grains.

Locality 12, near Kirkwood mine.—The occurrence of sudburite here was reported by Coleman.¹⁰

Regarding the distribution of the older norite or sudburite, Coleman¹¹ states "it is not known to occur anywhere in the district at a distance from the nickel range, but always at or near the margin of the nickel-bearing norite." The present writer found no exception to this statement. Sudburite is distinguished from the norite of the nickel intrusive by the nearly complete absence of quartz, the small amount of biotite, the abundance of mafic minerals, and the granoblastic texture.

ORIGIN

That sudburite is merely metamorphosed basic rock is shown by its typical granoblastic texture, by the stages in the recrystallization of plagioclase to granules, at first in small amount and later completely, and by the occurrence of amphibole with pyroxene granules developed in it. Stages in the development of pyroxene in amphibole may be seen in which only remnants of the latter mineral are left, these being completely surrounded by the former. Pyroxene granules have also formed in biotite. In the early stages of this alteration the original texture of the rock is retained, but in typical sudburite it is lost or greatly obscured. The writer saw no suggestion of any process other than recrystallization in the breakdown of the plagioclase to granules, and the alteration probably occurred without important changes in the chemical composition of the rock as a whole. Schwartz¹² gives an account of alteration in greenstone in northeastern Minnesota at the contact with the Duluth gabbro, to a rock there called "muscovadite." This term was introduced for the granular altered greenstones, altered sediments, and gabbro phase along the gabbro contacts; but later work showed it to be a contact metamorphic rock of both greenstones and sediments. Through the courtesy

¹⁰ *Ibid.*, p. 81.

¹¹ *Ibid.*

¹² G. M. Schwartz, "The Contrast in the Effect of Granite and Gabbro Intrusion on the Ely Greenstone," *Jour. Geol.*, Vol. XXXII (1924), p. 89.

of Dr. J. T. Stark, of Northwestern University, the present writer had an opportunity of examining sections of "muscovadite" and found them almost identical with Sudbury types. Sudburite is believed to have an origin similar to that of "muscovadite."

Sudburite is a rock formed through high-grade metamorphism. The intense conditions leading to the formation of this rock appear to have arisen from the intrusion of the nickel intrusive. The general position of the sudburite—nowhere far from the outer contact—supports this interpretation, though it might be expected that sudburite would occur more constantly and regularly around the contact. More work is needed to substantiate the interpretation.

The Froid-Stobie offset is separated from the intrusive by granites younger than the norite, highly metamorphosed graywackes, and greenstones. The sudburite in the offset is about a mile from the present outer norite contact. This is farther than might be expected if its formation is caused by the intrusive. It seems plausible to assume that the offset and the intrusive were once much closer and were separated by the later granite intrusion.

Wandke and Hoffman,¹³ in describing the alteration of basic inclusions in granite near Sudbury, give the breakdown of pyroxene and plagioclase to granules (giving essentially sudburite) as a stage in the granitization of the basic rock.

The writer did not examine rocks from the same place as those described by Wandke and Hoffman; but the sudburite, apparently similar to basic rock in a certain stage of alteration to granite, did not suggest a similar origin for it. Apart from the lack of any regular spacial arrangement of the granite, the type of change is different from that usually associated with granite intrusion. The only alteration of sudburite which the writer saw was to an amphibolite and not to a granite.

ALTERATION OF SUDBURITE

Alteration of sudburite by hornblende veinlets with preferential replacement of the pyroxene granules has been mentioned. In many places amphibole has replaced both pyroxene and plagioclase to a

¹³ A. Wandke and R. Hoffman, "The Sudbury Nickel Deposits, *Econ. Geol.*, Vol. XIX (1924), pp. 189-190.

great extent. This amphibolitization is not confined to the sudburite; it has also gone on in the norite near and at its outer contact, and in granites as near Sultana mine.

RELATION TO MINERALIZATION

The time relation of the formation of sudburite to the nickel-copper mineralization is important. Three possibilities are presented: the recrystallization took place before, during, or after mineralization. It is quite possible that a relation valid for one place may not hold true for another. In the sudburite near Gertrude mine and in the Frood offset, small quartz stringers with amphibole edges carry pyrrhotite and chalcopyrite, and these are abundant in the rock adjoining the vein. The sulphides corrode and replace the silicates. Amphibole veinlets often occur in the sudburite without accompanying mineralization. The few observations of the writer suggested that the same agents which caused the formation of amphibole, also brought in the ore minerals. This indicates that mineralization is subsequent to recrystallization.

REMARKS

It appears plausible to regard the formation of sudburite and its later alteration to amphibolite as two effects of the nickel intrusive. The first effect presumably arose from the change in physical conditions, principally the higher temperature, caused by the intrusive during and immediately after its intrusion in the rock adjacent to its outer contact. The second effect, after the intrusive had partly crystallized, was presumably caused by fluids emanating from it.

If the hypothesis which the writer advances for the formation of sudburite should prove correct, it may assist in solving some of the problems of the Sudbury area. Thus the apparently fresh lavas south of the Southern range are often puzzling to one unacquainted with the general geology of the Sudbury area, so much so that often one imagines an age difference between them and the more altered varieties (greenstones) close by. In reality the difference is due to a difference in metamorphism.

It appears to the writer that sudburite has not always been distinguished from the norite of the nickel intrusive, which has led to a

false picture of what the norite is. Thus, along the Southern range the norite near its outer contact always contains quartz but very little pyroxene (it has been changed to amphibole), and is usually considerably altered.

Any rock in which sudburite or recrystallization products of a similar type appropriate to its mineralogical composition occur is older than the nickel intrusive. Possibly this may serve as a criterion for distinguishing between granites younger and older than the intrusive. Older granites might be expected to show recrystallization close to the intrusive, whereas younger granites would not. Furthermore, sudburite inclusions would indicate that the granite was younger.

The formation of sudburite indicates the intense conditions prevailing during the intrusion of the intrusive. Its extent indicates the distribution of these conditions. If sudburite should be found far from the intrusive, it would indicate that it had been moved there after formation.

ACKNOWLEDGMENTS

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